STATUS AND FUTURE PROSPECTS OF LEPTON UNIVERSALITY TESTS AT LHCb

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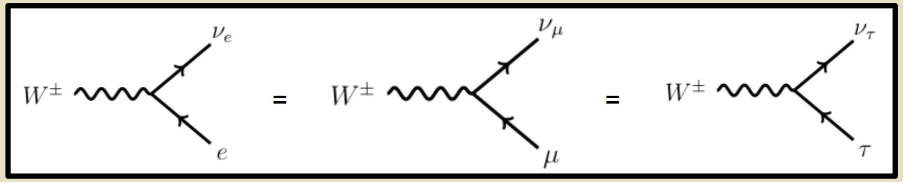
On behalf of the LHCb Collaboration

"I suppose I'll be the one to mention the elephant in the room."

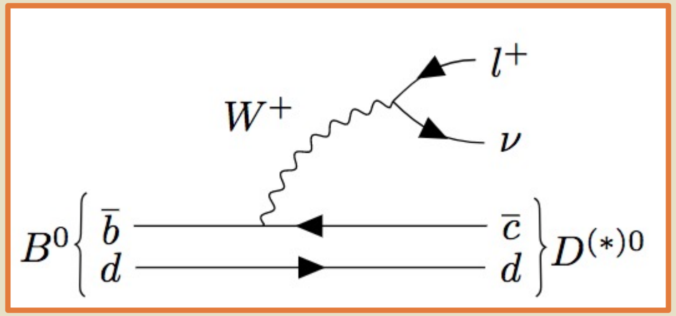
NuFACT 2022, August 1-6 2022

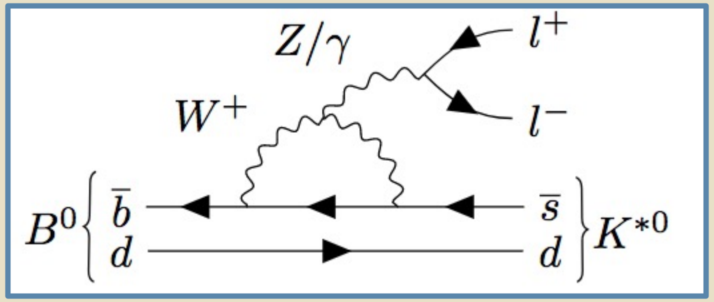
Lepton Flavour Universality

- Standard Model features **Lepton Flavour Universality (LFU)**: accidental symmetry of the SM
  - Equal electroweak coupling of gauge bosons to all charged leptons.
- Difference in dynamics driven solely by the **difference in the masses $m_e < m_\mu \ll m_\tau$**



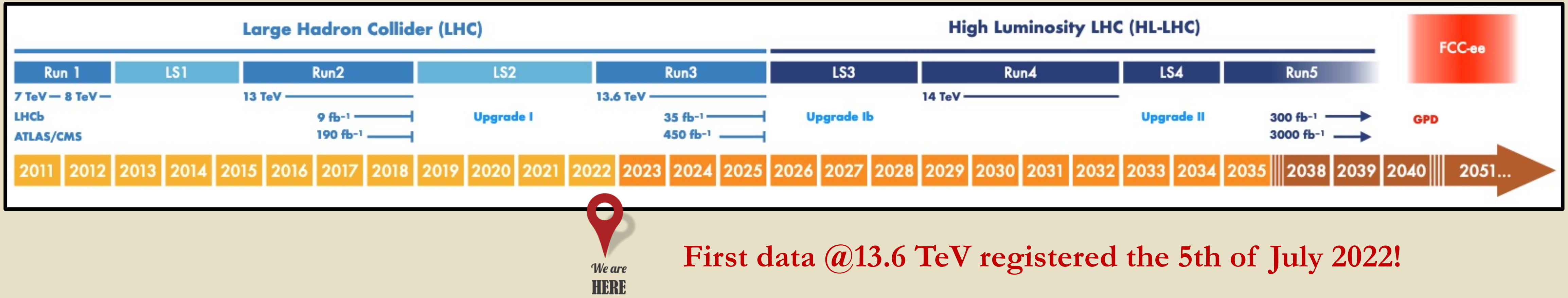
- In this presentation: **intriguing hints of anomalies** in b-hadron decays observed by different experiments in





Flavour-changing CHARGED current $(b \to c\ell\bar{\nu})$ **Flavour-changing NEUTRAL current** $(b \to s(d)\ell^+\ell^-)$

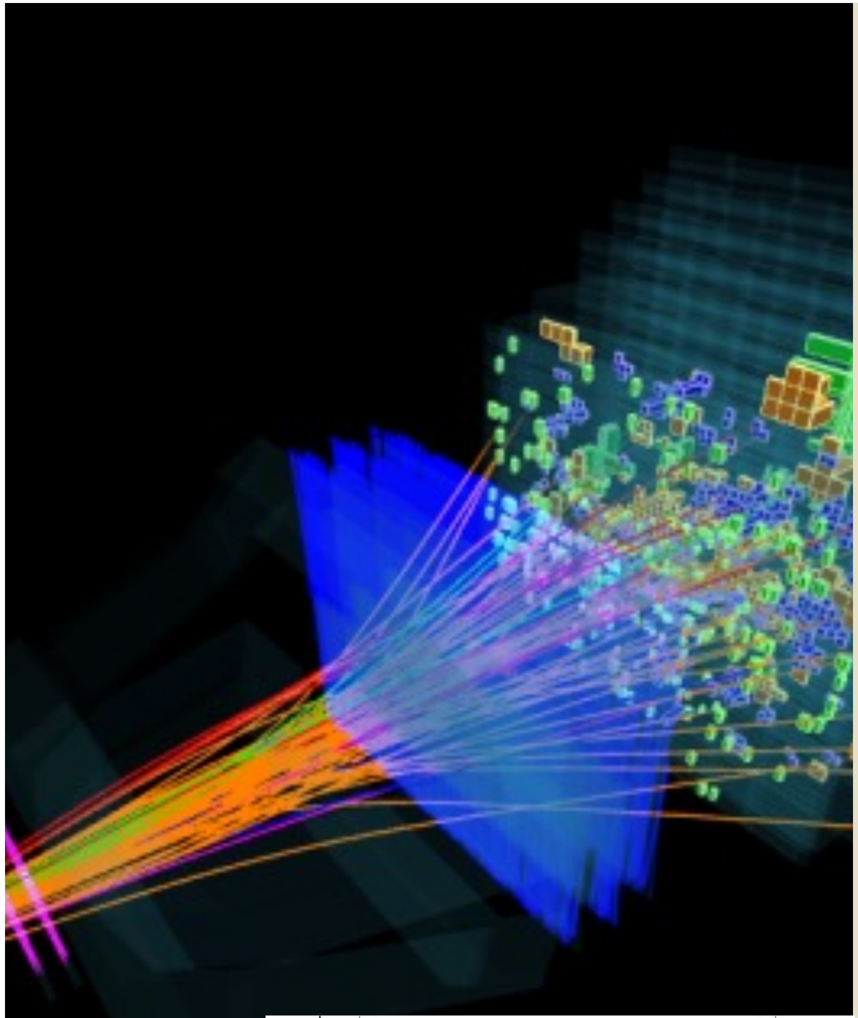
The experimental scenario

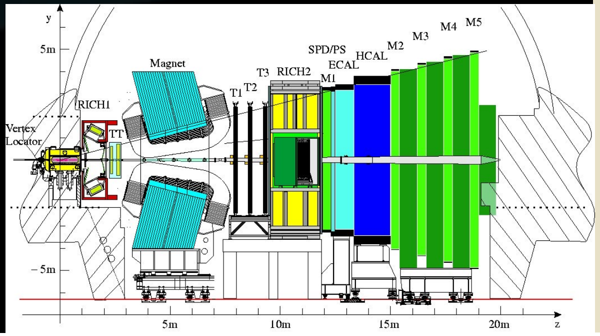


First data @13.6 TeV registered the 5th of July 2022!

LHCb Run 3 + 4: [LHCb Upgrade Physics Document]

- Major upgrades of all sub-detectors
- $\mathcal{L}_{\text{peak}} = 2{\times}10^{33}\text{cm}^{-2}\text{s}^{-1}$, # of pp interactions ~5
- Fully software trigger, readout @40MHz, hadronic yield x10 relative to Run 2 [CERN-LHCC-2020-006]





Flavour physics @LHCb Run 1-2

Single arm spectrometer designed for high precision flavour physics measurements [J. INST. 3 (2008) S08005]

- Pseudorapidity range $\eta \epsilon$ [2,5]

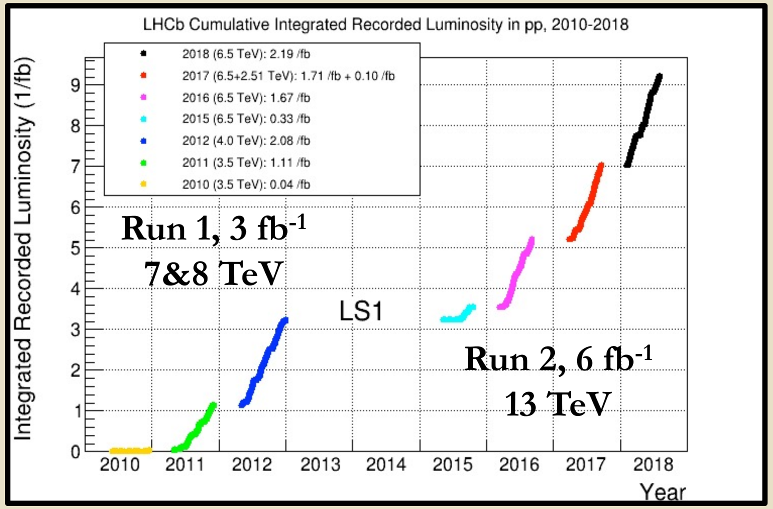
◦ # of Primary Vertices ~ 2

◦ Decay time res: ~45 fs

◦ IP res: ~20 μm for high p_T

◦ Highly eff. Particle IDentification

◦ Excellent primary and secondary vertex reconstruction [INT.J.MOD.PHYS A30 (2015) 1530022]



Large number of beauty hadrons within LHCb acceptance:

$\sigma_{b\bar{b}}$(7 TeV) = 72.0 ± 0.3 ± 6.8 μb

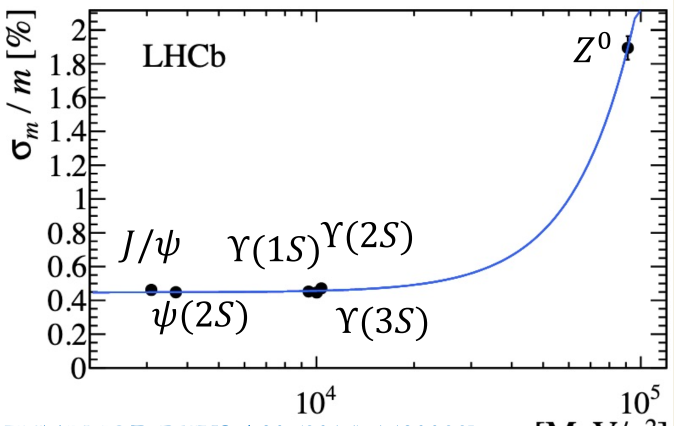
$\sigma_{b\bar{b}}$(13 TeV) = 154.3 ± 1.5 ± 14.3 μb

[PRL 118 (2017) 052002]

LEPTONS RECONSTRUCTION @LHCb

MUONS

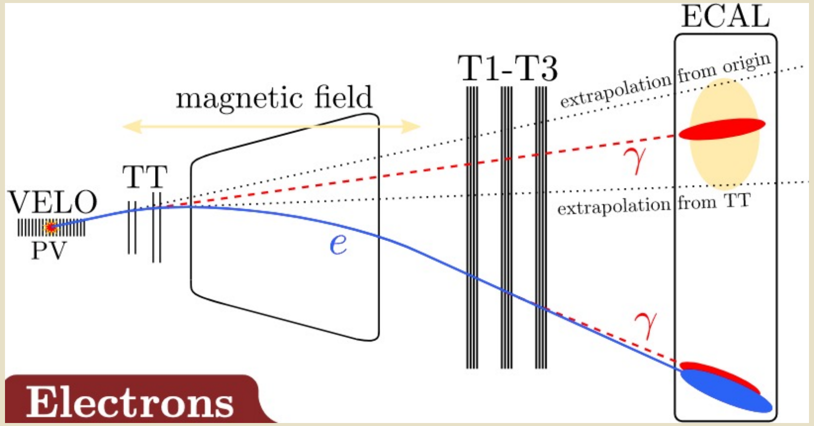
- Dedicated muon chambers
  - Clear trigger and PID
- Very efficient tracking system
- Very good di-muon resolution



[INT.J.MOD.PHYS A30 (2015) 1530022]

ELECTRONS

- Higher occupancy in calorimeter
  - Higher trigger thresholds than for μ
- Bremsstrahlung emission:
  - Degradation of B mass resolution
  - Large partially reconstructed bkg
  - Recovery not 100% efficient



[JINST 14 (2019) P11023]

TAUS

- Missing energy from ν degrading the resolution
- τ vertex not easy to identify in prompt decays
- More background polluting the mass distr.

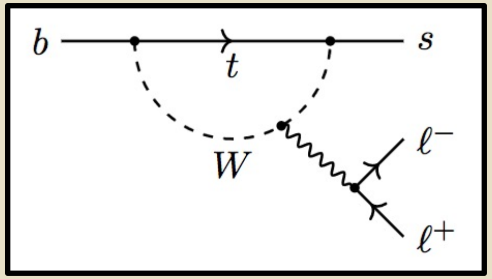
τ decay	BR(%)
$\tau^+ \to \mu^+(e^+)\nu\nu$	$17.39(.82) \pm 0.04$
$\tau^+ \to \pi^+\nu$	10.82 ± 0.05
$\tau^+ \to \pi^+\pi^0\nu$	25.49 ± 0.09
$\tau^+ \to \pi^+\pi^0\pi^0\nu$	9.26 ± 0.10
$\tau^+ \to \pi^+\pi^+\pi^-\nu$	9.31 ± 0.05
$\tau^+ \to \pi^+\pi^+\pi^-\pi^0\nu$	4.62 ± 0.05

RARE DECAYS

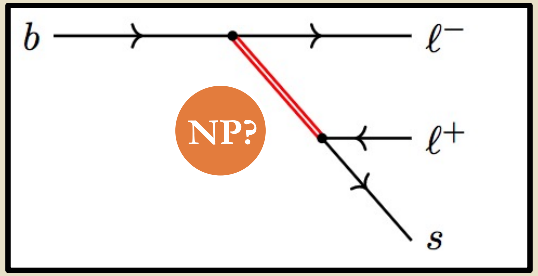
Rare decays as probe for NP

- Rare FCNC decays are **loop-suppressed** in the SM ($\mathcal{B} \sim 10^{-6} - 10^{-7}$ or less)
- New heavy particles (NP) can significantly contribute, affecting decay rates and angular distributions

Standard Model



New Physics

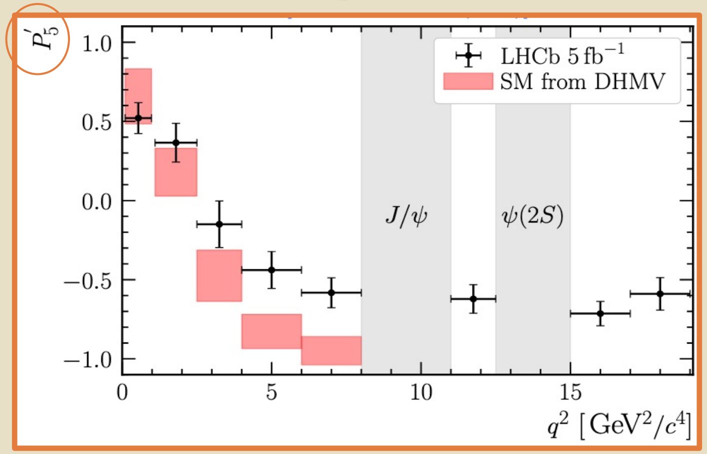


Intriguing **tensions** w.r.t. the SM, e.g.

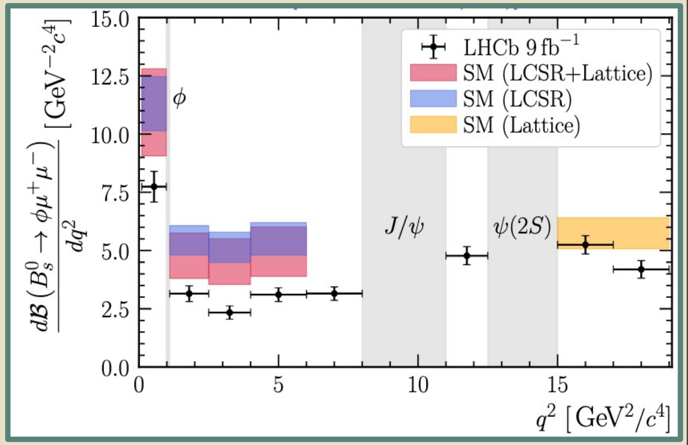
- **Angular analyses**, e.g. $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 011082 (2020)]
- **Branching fractions**, e.g. $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 151801 (2021)]

- **Tensions at 1-3 σ**
- **But**: sizeable **hadronic theory uncertainties** of SM predictions, more data always welcome

Less form-factor dependent observable



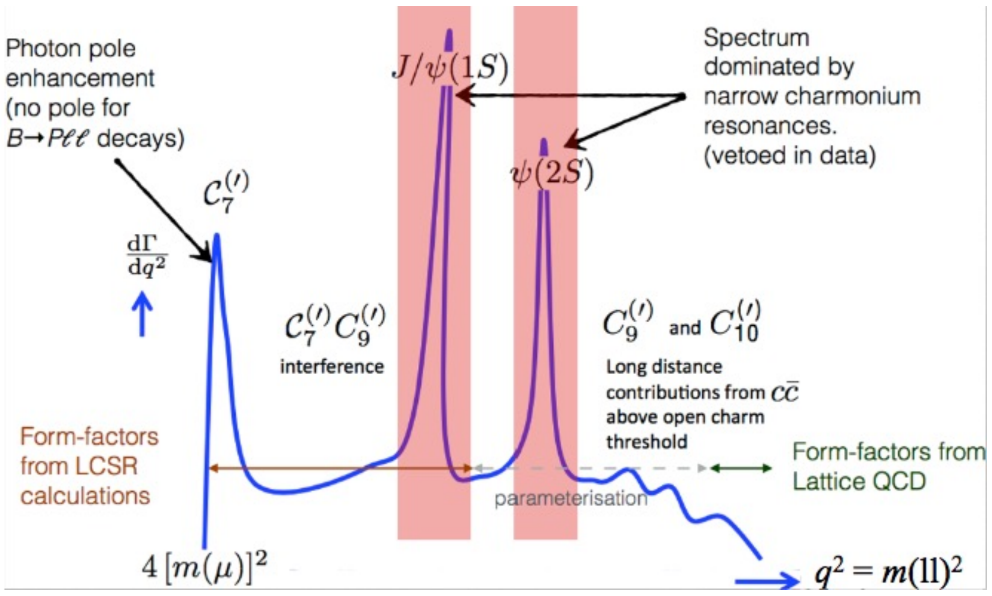
[PRL 125 011082 (2020)]



[PRL 127 151801 (2021)]

$$q^2 = m(\ell^+\ell^-)^2$$

Tests of LFU @LHCb



$q^2 = m(\ell^+\ell^-)^2$, inv. mass of di-lepton system

$C_i^{(\prime)}$ is the LH (RH) **Wilson coefficient** with:

i=1,2 Tree
***i*=7 Photon penguin**
i=S,P (Pseudo)scalar penguin
i=3-6,8 Gluon Penguin
***i*=9,10 EW penguin**

- Double ratio of the rare to the J/ψ reduces syst. unc. (LFU established at ‰ level [PDG 2022]):

$$R_H = \frac{\mathcal{B}(B\to H_s\mu^+\mu^-)}{\mathcal{B}(B\to H_s e^+e^-)} \times \frac{\mathcal{B}(B\to H_s\,J/\psi(e^+e^-))}{\mathcal{B}(B\to H_s J/\psi(\mu^+\mu^-))}$$

$$= 1 \pm \mathcal{O}(1\%)$$ [Eur. Phys. J. C 76, 440 (2016)]

with $H_s = K^+, K^{*0}, K_S^0, K^{*+}, \ldots$

- In order to remove long distance effects (i.e. $b\to(c\bar{c}\to\ell^+\ell^-)s$) the narrow charm. resonances are vetoed and used to **validate the analysis**: $r_{J/\psi}$ - $R_{\psi(2S)}$
- **Hadronic uncertainties cancel in the ratio**
- **Main complexity**: muons and electrons behave very differently in the detector, but double ratio helps.
- Blind analyses

Analysis validation

Validation

- Validation using ratio of resonant branching fractions

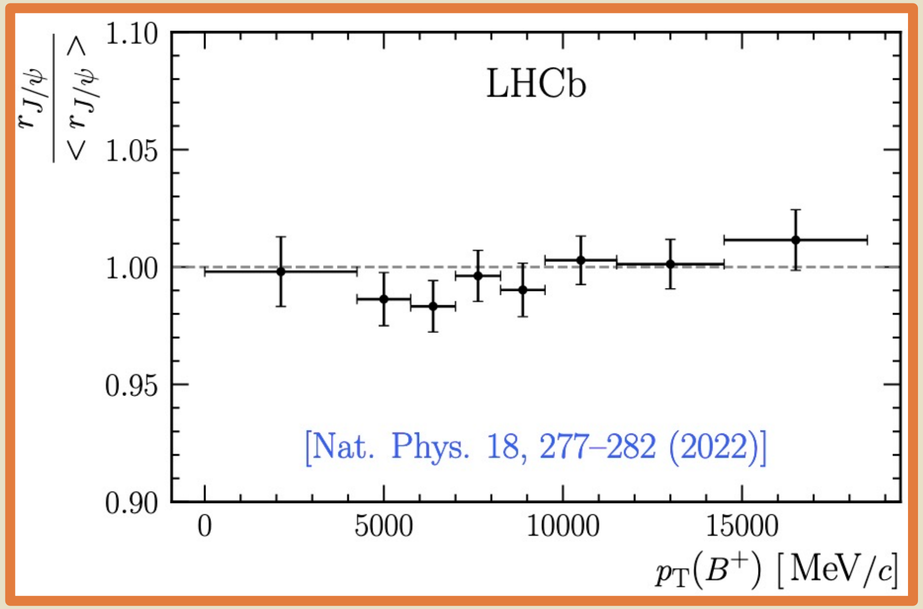
$$r_{J/\psi} = \frac{\mathcal{B}(B_q \to H_s J/\psi(\mu^+\mu^-))}{\mathcal{B}(B_q \to H_s J/\psi(e^+e^-))} \quad \text{and} \quad R_{\psi(2S)} = \frac{\mathcal{B}(B_q \to H_s \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B_q \to H_s \psi(2S)(e^+e^-))} \cdot r_{J/\psi}^{-1}$$

- Using the analysis of R_K as an example [Nat. Phys. 18, 277-282 (2022)]

The ratio $r_{J/\psi}$

Single ratio of branching fractions

- Probe electrons directly versus muons
- Limited cancellation of systematics⇒ Stringent validation
- $r_{J/\psi} = 0.981 \pm 0.020$ (stat $\oplus$ syst)
- Independent of kinematics



Analysis validation

Validation

- Validation using ratio of resonant branching fractions

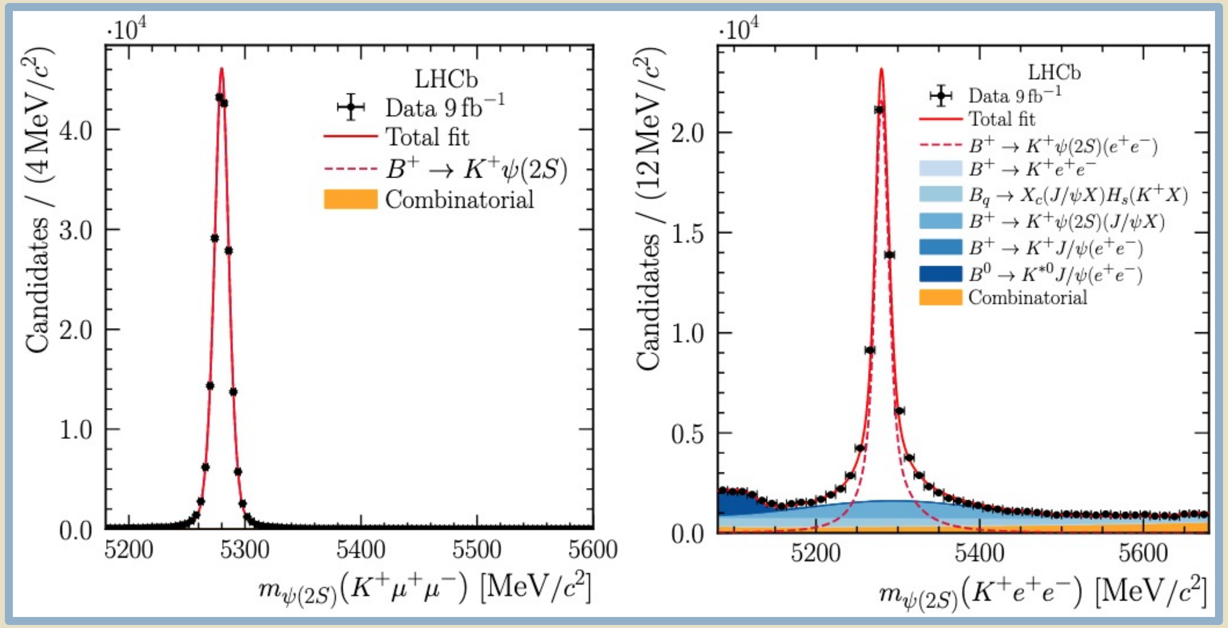
$$r_{J/\psi} = \frac{\mathcal{B}(B_q \to H_s J/\psi(\mu^+\mu^-))}{\mathcal{B}(B_q \to H_s J/\psi(e^+e^-))} \quad \text{and} \quad R_{\psi(2S)} = \frac{\mathcal{B}(B_q \to H_s \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B_q \to H_s \psi(2S)(e^+e^-))} \cdot r_{J/\psi}^{-1}$$

- Using the analysis of R_K as an example [Nat. Phys. 18, 277-282 (2022)]

The ratio $R_{\psi(2S)}$

Double ratio of branching fractions

- Measured like R_H
- Same cancellation of systematics
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat $\oplus$ syst)



Measurement of R_{K^+}

- Decay used: $B^+ \to K^+\ell^+\ell^-$
- Measured in $q^2 \in [1.1, 6.0\ \mathrm{GeV}^2/c^4]$
- Using Run1 + Run 2, but still statistically limited
- Biggest systematic: fit model ~1%

Validation

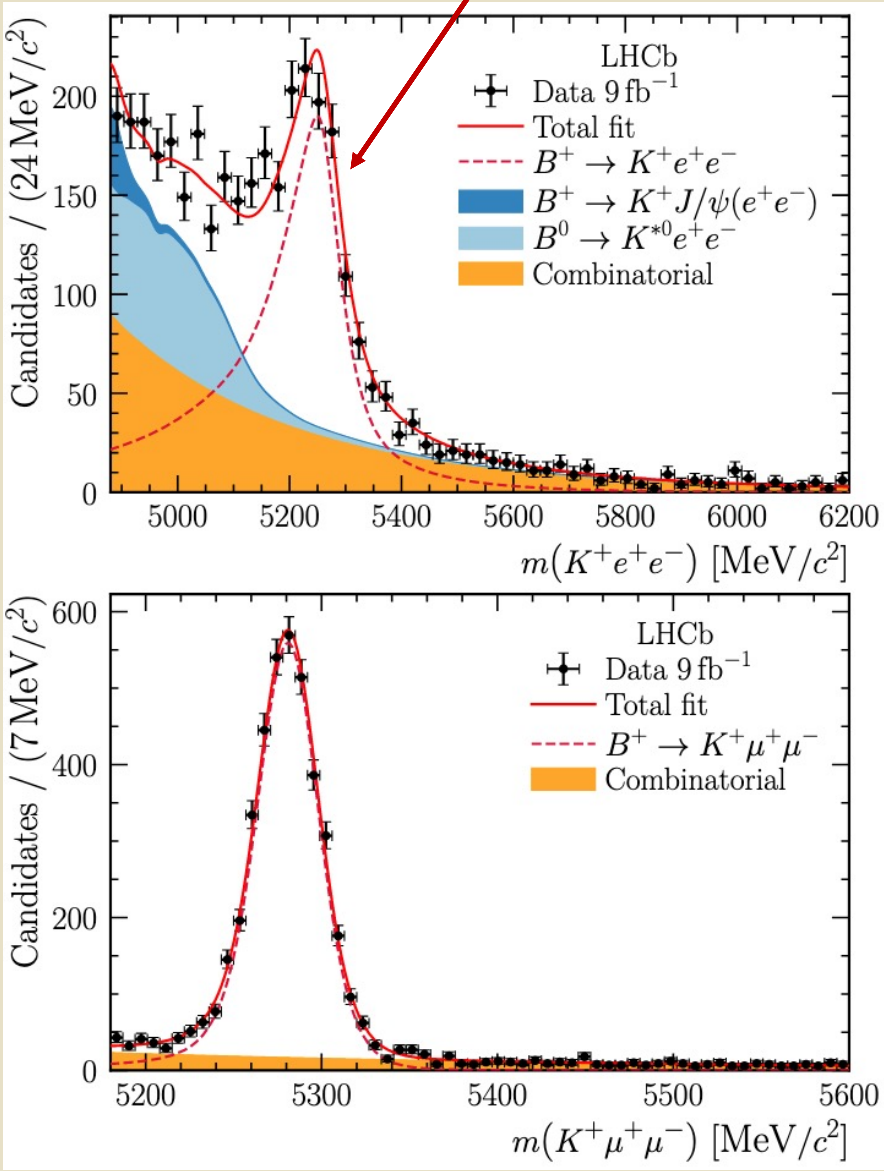
- $r_{J/\psi} = 0.981 \pm 0.020$ (stat $\oplus$ syst)
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat $\oplus$ syst)

Result

- $\boldsymbol{R_{K^+} = 0.846^{+0.042}_{-0.039}(\mathrm{stat})^{+0.013}_{-0.012}\,(\mathrm{syst})}$
- Tension of **3.1σ wrt the SM**

[Nat. Phys. 18, 277-282 (2022)]

resolution due to bremsstrahlung emission & recovery



Measurement of $R_{K_S^0}$

- Decay used: $B^0 \to K_S^0 \ell^+ \ell^-$
- Measured in $q^2 \in [1.1, 6.0\ \mathrm{GeV}^2/c^4]$
- Using Run1 + Run 2, but still statistically limited
- Biggest systematic: simulation size ~2-3%

Validation

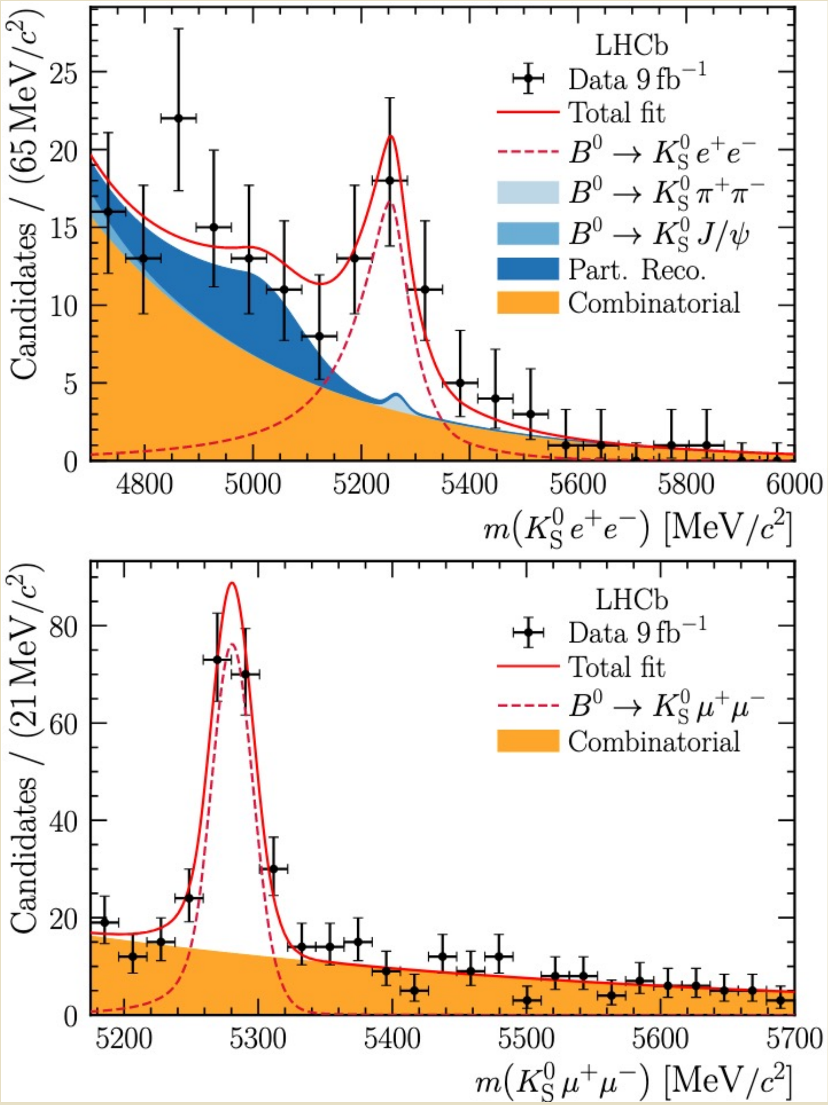
- $r_{J/\psi}^{-1} = 0.977 \pm 0.008\ (\mathrm{stat}) \pm 0.027\ (\mathrm{syst})$
- $R_{\psi(2S)}^{-1} = 1.014 \pm 0.030\ (\mathrm{stat}) \pm 0.020\ (\mathrm{syst})$

Result

- $\boldsymbol{R_{K_S^0} = 0.66^{+0.20}_{-0.14}(\mathrm{stat})^{+0.02}_{-0.04}\ (\mathrm{syst})}$
- Agreement with SM at **1.5σ** level

[PRL 128, 19 (2022)]

First observation of rare electron mode



Measurement of $R_{K^{*+}}$

- Decay used: $B^+ \to K^{*+}\ell^+\ell^-$
- Measured in $q^2 \in [0.045, 6.0\ \mathrm{GeV}^2/c^4]$
- Using Run 1 + Run 2, but still statistically limited
- Biggest systematic: simulation size ~2-3%

Validation

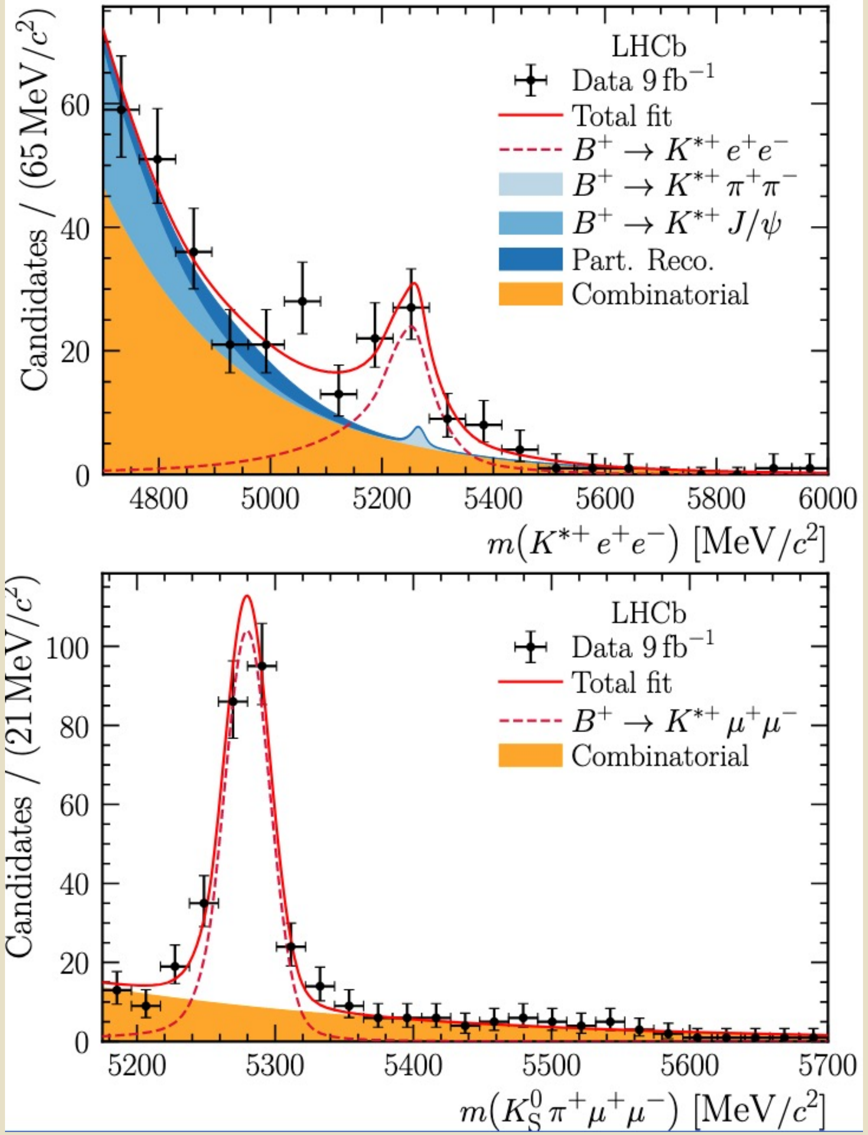
- $r_{J/\psi}^{-1} = 0.965 \pm 0.011\ (\mathrm{stat}) \pm 0.032\ (\mathrm{syst})$
- $R_{\psi(2S)}^{-1} = 1.017 \pm 0.045\ (\mathrm{stat}) \pm 0.023\ (\mathrm{syst})$

Result

- $\boldsymbol{R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}\ (\mathrm{syst})}$
- Agreement with SM at **1.4σ** level

[PRL 128, 19 (2022)]

First observation of rare electron mode



Measurement of R_{pK}

- Decay used: $\Lambda_b \to pK^-\ell^+\ell^-$
- Measured in $q^2 \in [0.1, 6.0\ \mathrm{GeV}^2/c^4]$ and $m(pK^-) < 2600\ \mathrm{MeV}/c^2$
- Using Run 1+2016, still statistically limited
- Biggest systematic: fit model ~5%

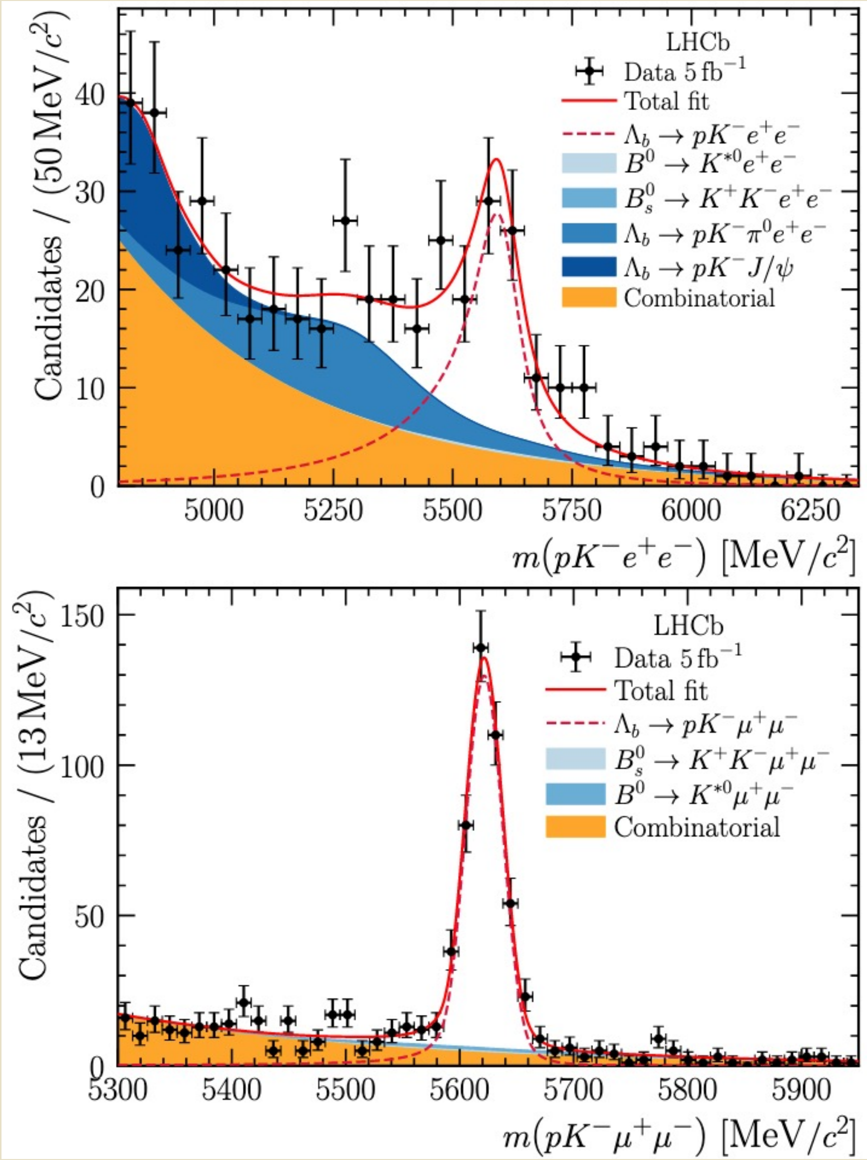
Validation

- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$ (stat $\oplus$ syst)
- $R_{\psi(2S)}$ compatible with unity whitin 1σ

Result

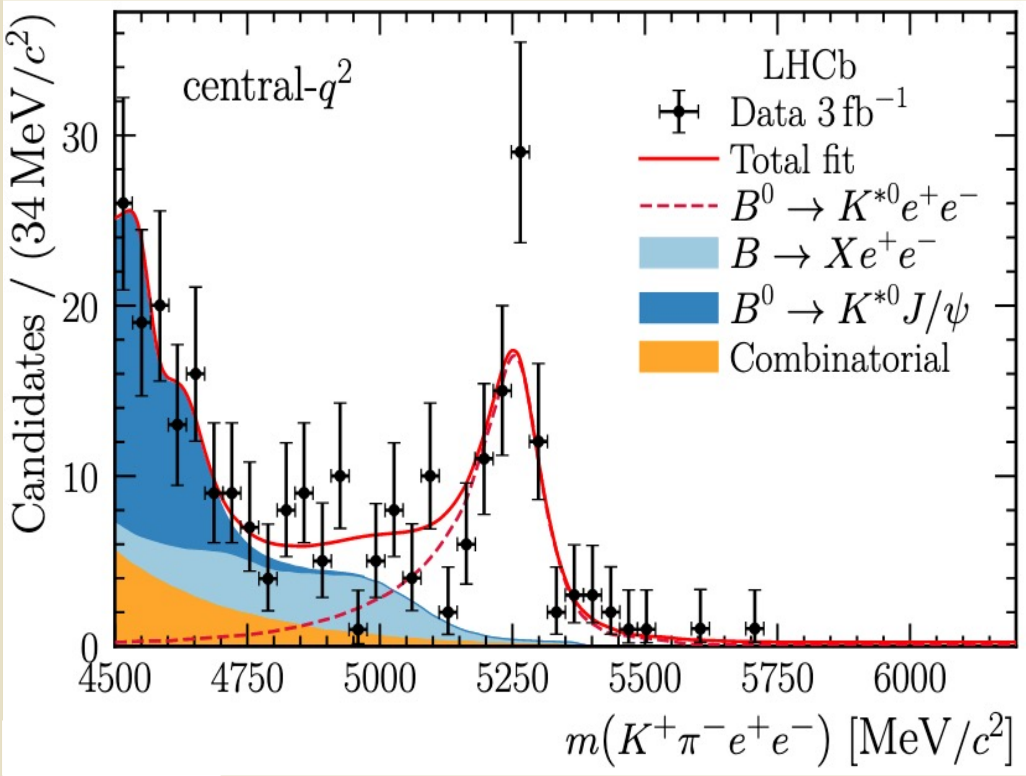
- $\boldsymbol{R_{pK} = 0.86^{+0.14}_{-0.11}(\mathrm{stat}) \pm 0.05(\mathrm{syst})}$
- Agreement with SM at **<1σ** level

[JHEP 05, 040 (2020)]



Measurement of $R_{K^{*0}}$

- Decay used: $B^0 \to K^{*0}\ell^+\ell^-$
- Two separate q^2-regions:
  - $q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2/c^4$: **low q^2**
  - $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$: **central q^2**
- Using Run 1, still statistically limited
- Biggest systematic:
  - **low q^2**: simulation calibration (2-5)%
  - **central q^2**: residual backgrounds 5%



Validation

- $r_{J/\psi} = 1.043 \pm 0.006\ (\mathrm{stat}) \pm 0.045\ (\mathrm{syst})$
- $R_{\psi(2S)}$ compatible with unity whitin 1σ

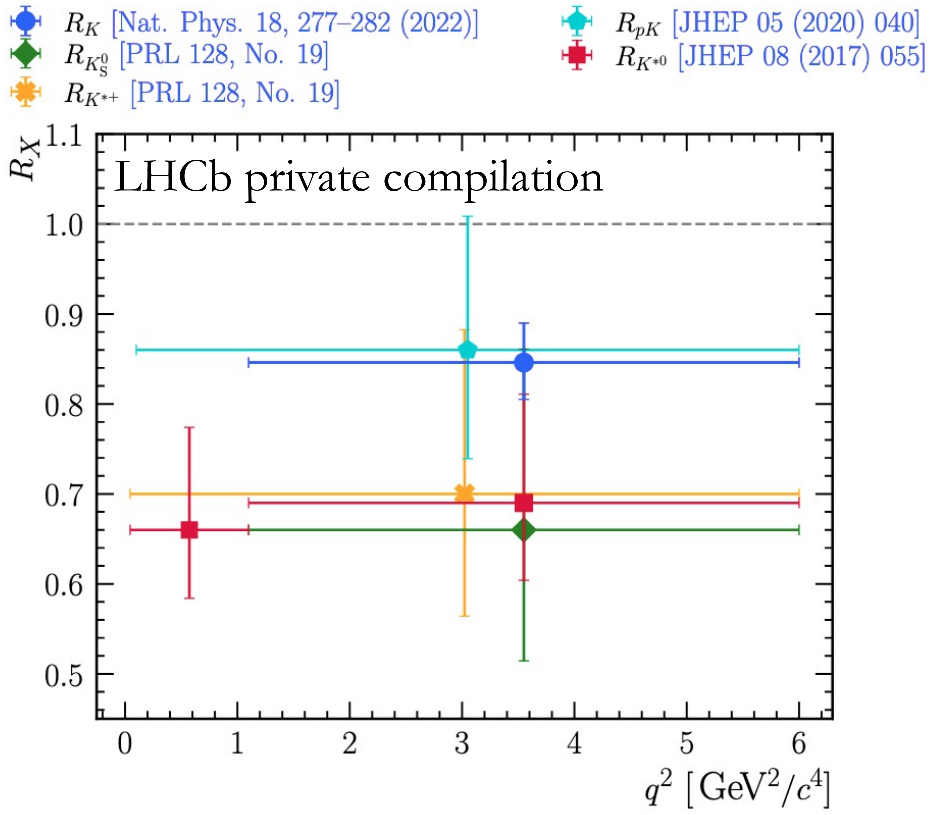
Results for $R_{K^{*0}}$

low q^2: $0.66^{+0.11}_{-0.07}(\mathrm{stat}) \pm 0.03(\mathrm{syst})$
central q^2: $0.69^{+0.11}_{-0.07}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$

- Tension with SM at **2.1σ** and **2.4σ** level

[JHEP 08, 055 (2017)]

$b \to s\ell^+\ell^-$ summary



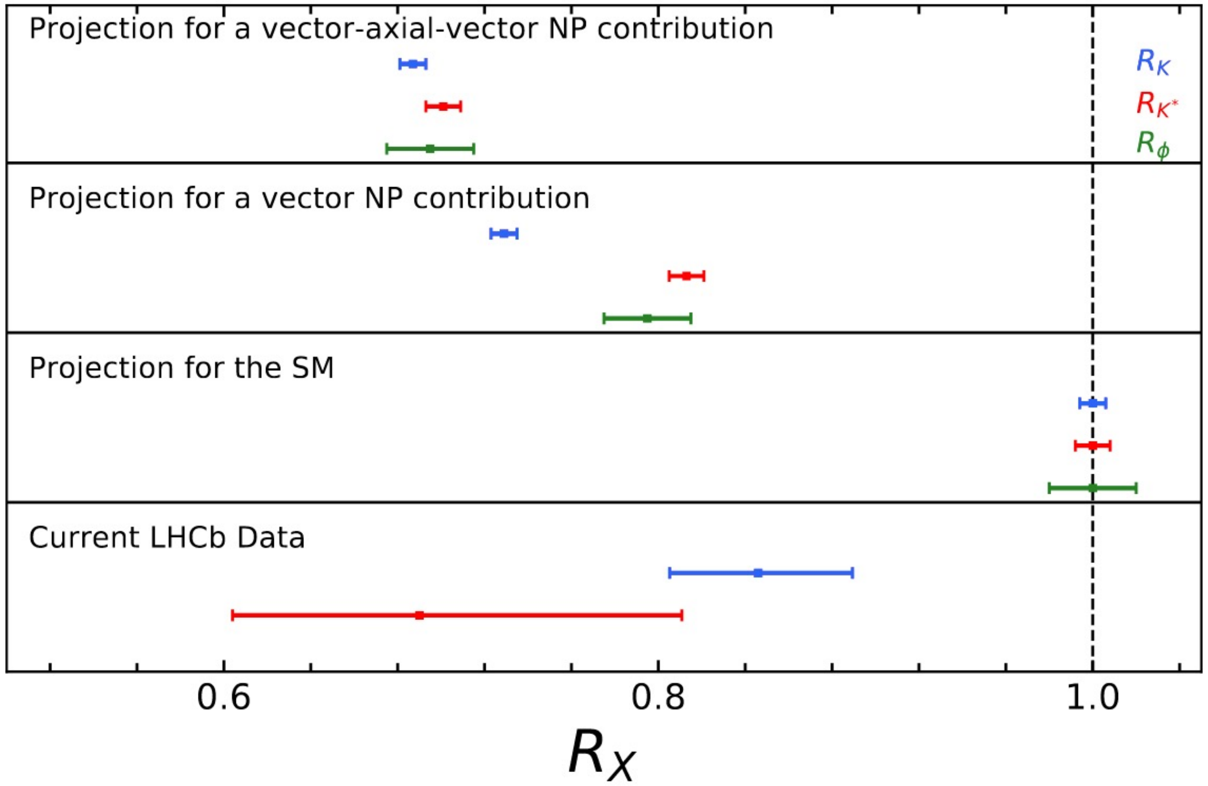
[S. Schmitt talk @ICHEP 2022]

- Intriguing **tensions observed in some channels**

Needs confirmation with a larger dataset!

- Most results from **partial LHCb dataset**
- In particular, LHCb is currently focused on a **combined measurement of R_{K^+} and $R_{K^{*0}}$** with the Run 1+2 legacy dataset
  - This leads to a deeper understanding of systematic effects which will be reflected in the final result.
  - Please be patient for the final results!
- Measurements of $R_{pK}, R_\phi, R_{K\pi\pi}$ and more with full 9 fb^{-1} dataset ongoing

Inputs from independent experiments are also crucial!



[LHCb Upgrade II TDR]

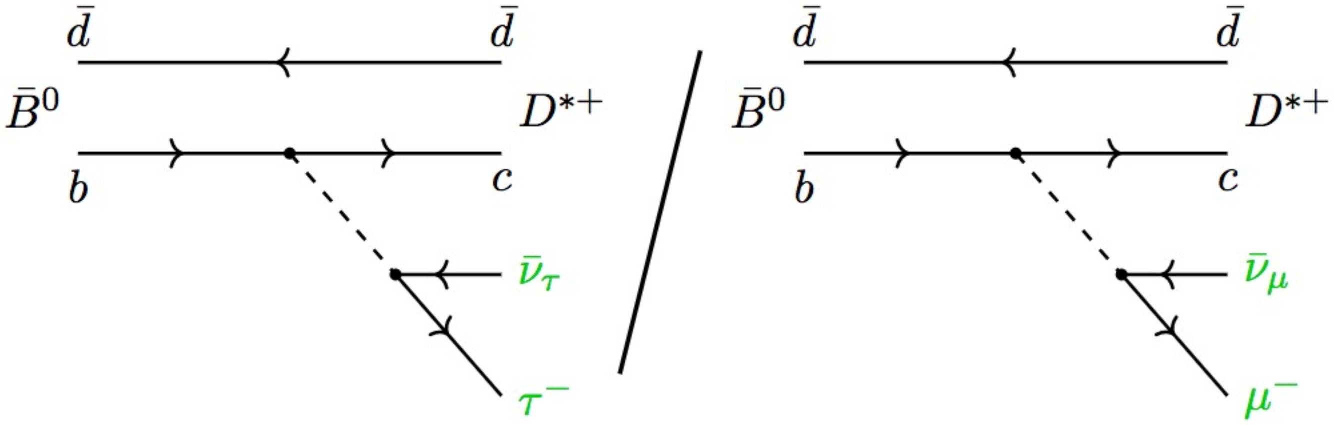
Future prospects

- Precision on $\boldsymbol{R_K}$ **and** $\boldsymbol{R_{K^{*0}}}$ will be **~2.5% and 2% with ~23 fb^{-1} and ~50 fb^{-1}**
- Projected sensitivity with the LHCb **Upgrade II** detector, with ~300 fb^{-1}
- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-}$~46 000, $N_{K^{*0}e^+e^-}$~20 000
- Ultimate precision on $\boldsymbol{R_K}$ **and** $\boldsymbol{R_{K^{*0}}}$ **will be better than 1%**

[LHCb Upgrade Physics Document]
PUB-2018-009

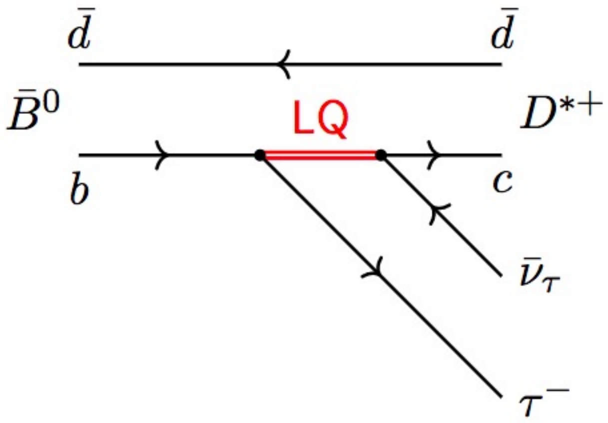
CHARGED CURRENT TREE-LEVEL

SEMI-LEPTONIC DECAYS



Ratios sensitive to possible NP coupling mainly to the 3rd generation (e.g. Leptoquarks):

[PRL 116, 081801, PRD 94, 115201]



Tests of LFU @LHCb

- LFU probed using the ratio:

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell \bar{\nu}_\ell)}$$

with $H_c = \boldsymbol{D^{*+}}, D^0, D^+, D_s^+, \boldsymbol{\Lambda_c^+}, \boldsymbol{J/\psi}$ ... and $H_b = \boldsymbol{B^0}, B_s^0, \boldsymbol{B_{(c)}^+}, \boldsymbol{\Lambda_b}$ **,** but LHCb could also exploit Ξ_b, Ω_b, etc

- $B_s^0, B_{(c)}^+, \Lambda_b, \Xi_b, \Omega_b$ only at LHCb
- $\ell = \mu$ LHCb, $\ell = e/\mu$ B-factories

- **Neutrinos not detected, approximations used for signal reconstruction and large MCs needed for template shapes**
- Semileptonic decays theoretical predictions are precise (% level)
- Large BR

Current experimental status $R(D) - R(D^*)$

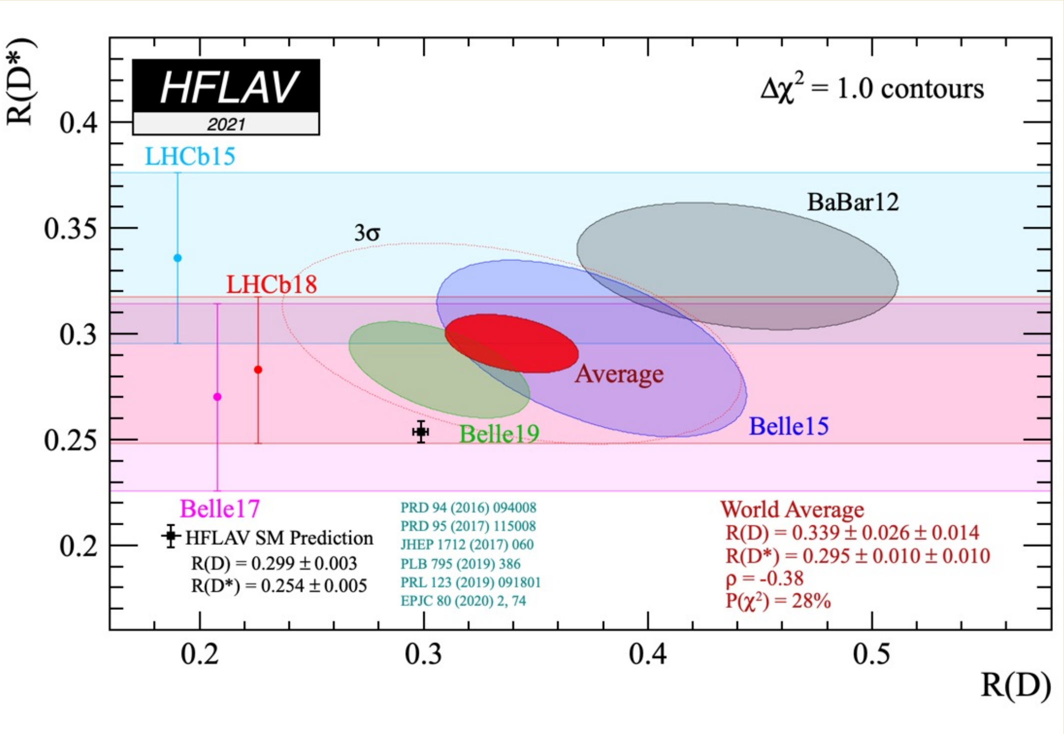
LHCb has performed analysis of $R(D^*)$ only

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^* \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^* \mu^+ \nu_\mu)}$$

- with **muonic** $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$ using Run 1:
  $\boldsymbol{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$
  [PRL 115, 111803 (2015)]
  2.1σ above SM

- With **3-prong hadronic** $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\,\bar{\nu}_\tau$ using Run 1:
  $\boldsymbol{R(D^*) = 0.280 \pm 0.018 \pm 0.026 \pm 0.013}$
  [PRL 120, 171802 (2018)] [PRD 97, 072013 (2018)]
  1σ above SM

Belle and BaBar saw hints since ‘12. LHCb now a major player.



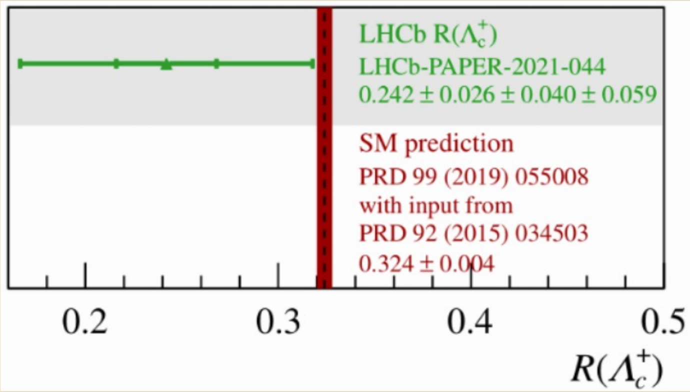
- All measurements are above SM predictions.
- Deviation of $R(D)$ and $R(D^*)$ combination **from SM predictions ~3.3σ**

Current experimental status $R(\Lambda_c^+)$

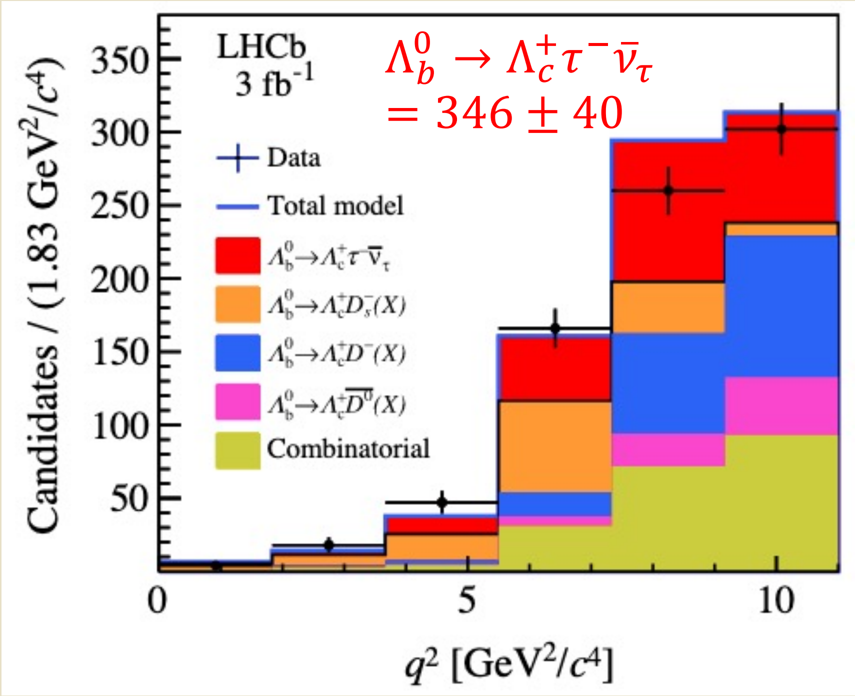
LHCb has performed analysis of

$$R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

- First **LFU test** in a **baryonic** $b \to c\ell\nu$ decay
  - Initial state spin ½ → could couple to different physics beyond the SM
- With **3-prong hadronic** $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ using Run 1:
  $\boldsymbol{R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})}$*
  [PRL 128, 191803 (2022)]
- To be compared with the SM prediction: $R(\Lambda_c^+) = 0.324 \pm 0.004$
  [PRD 99, 055008 (2019)]



Agreement with SM within 1σ



First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with 6σ significance

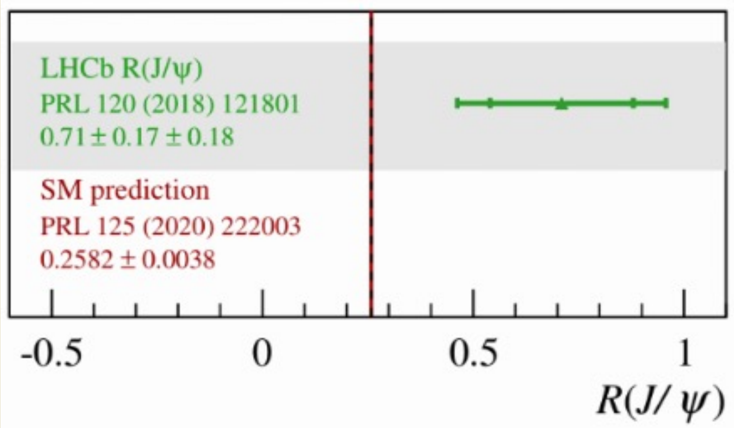
* Measured relative to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

Current experimental status $R(J/\psi)$

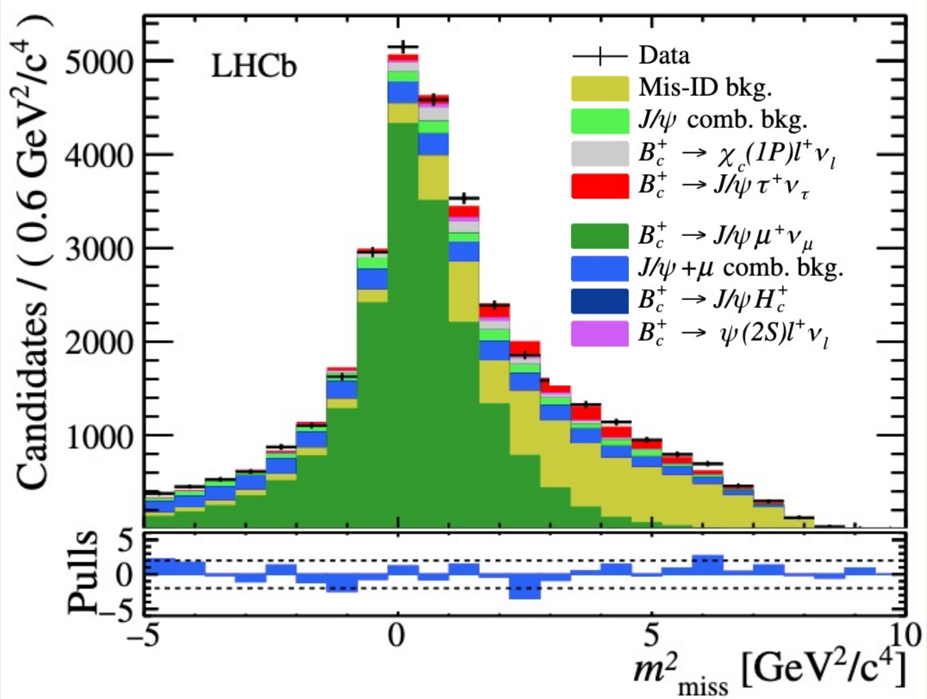
LHCb has performed analysis of

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

- With **muonic** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ using Run 1:
  $\boldsymbol{R(J/\psi) = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})}$
  [PRL 120, 121801 (2018)]
- To be compared with the SM prediction: $R(J/\psi) = 0.2582 \pm 0.0038$
  [PRL 125, 222003 (2020)]



2σ above the SM



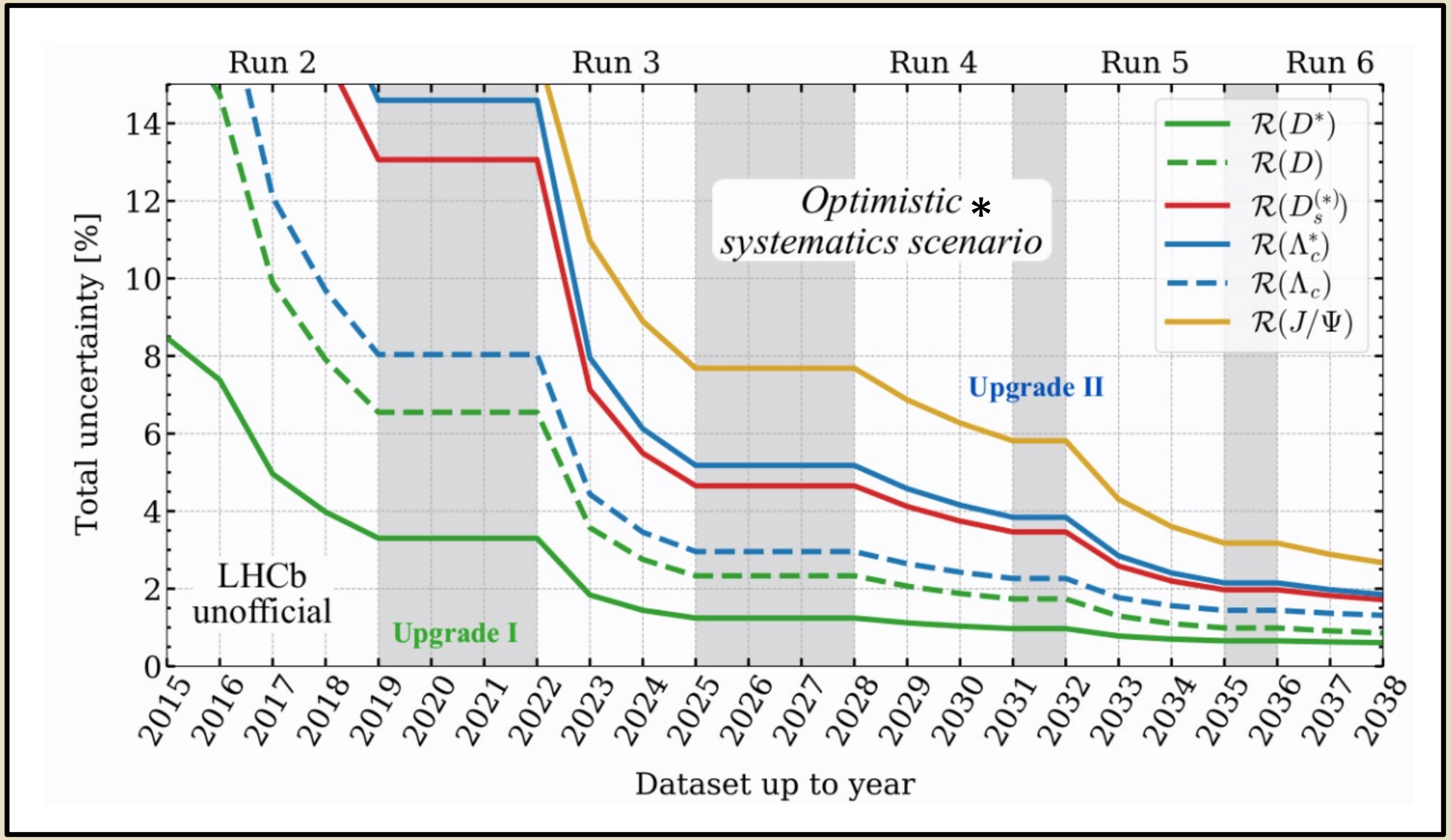
$\boldsymbol{B_c^+ \to J/\psi\tau^+\nu_\tau = 1400 \pm 300}$

Observation of $B_c^+ \to J/\psi\tau^+\nu_\tau$ with 3σ significance accounting also for systematics

Prospects

LHCb plans to include also:

- $R(D^{+})$
- $R(D^{*}) - (e - \mu)$
- Combined $R(D^{*}) - R(D^{0})$
- $R(D^{**})$
- $R(D_s^{*})$
- $R(\Lambda_c^{**})$



[Rev. Mod. Phys. 94, 015003][arXiv:1808.08865]

- Exploring new observables beyond the branching fraction ratios, e.g. **angular observables** to determine spin structure of potential new physics

* Irreducible systematic uncertainty of 0.5% on $R(D^{(*)})$ and 2% on the other ratios

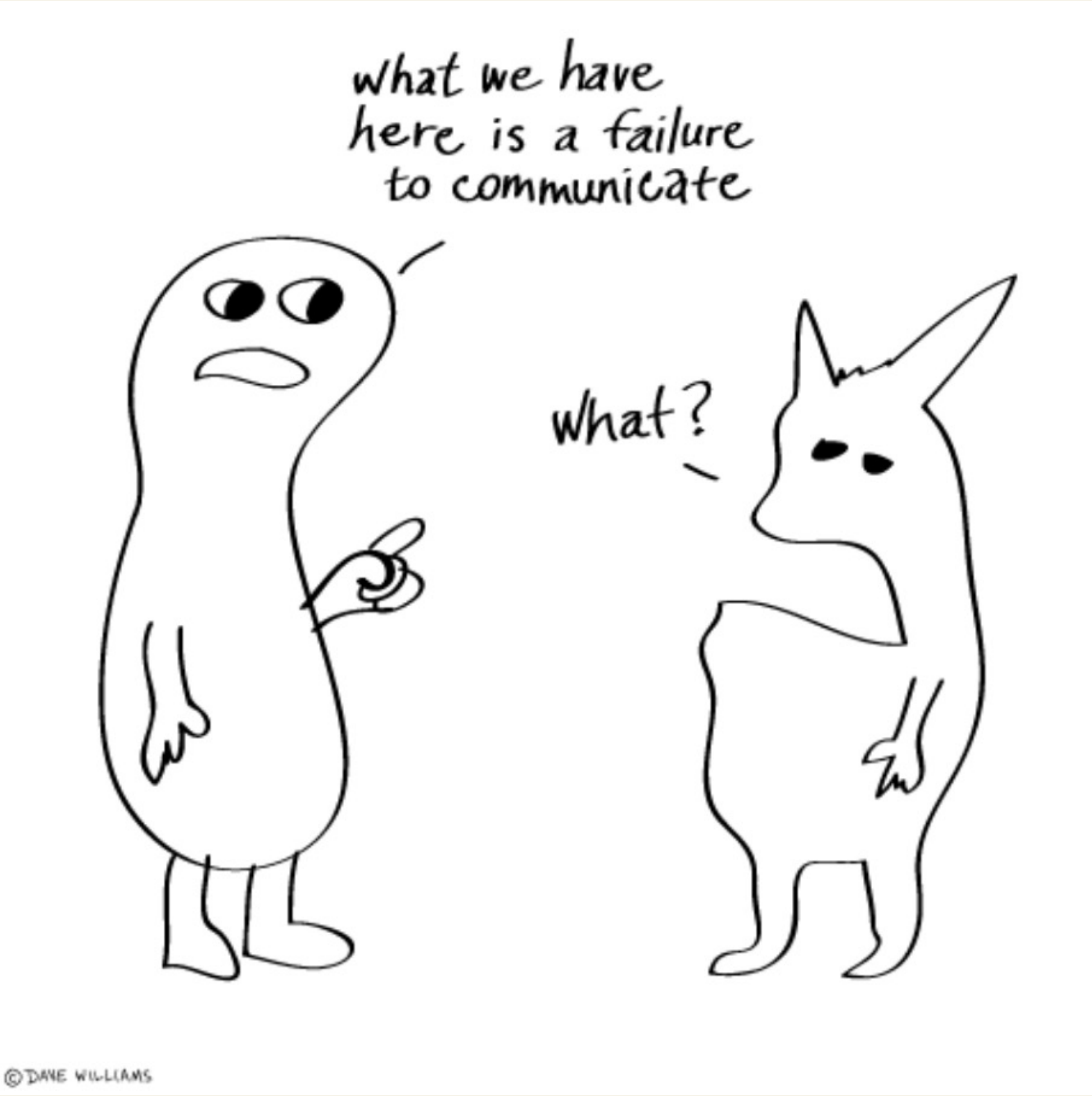
Conclusions

- LHCb has measured several LFU observables.
- Intriguing **hints of anomalies** in some b-hadron decays, powerful probes of the SM!
- More measurements using full Run 1+2 dataset in preparation and using new channels.
- Most analyses are **statistically dominated**: data from the LHCb upgrade will further improve these measurements, helping clarifying the picture.
- **Run 3 just started**, hopefully exciting news soon!!
- If true, hugely important for the future development of high-energy particle physics, providing a **clear target for future searches at energy frontier**… exactly what's missing right now!

… but even if not confirmed, they serve as a good example of the potential of Flavour Physics at Upgrade II to probe beyond the energy frontier.

Thanks for your attention!

"Welcome! Today's topic is 'How To Give A Presentation Without Losing Your Audience's Attention'. The End. Thank you for coming."


what we have here is a failure to communicate
what?
©DAVE WILLIAMS

BACKUP

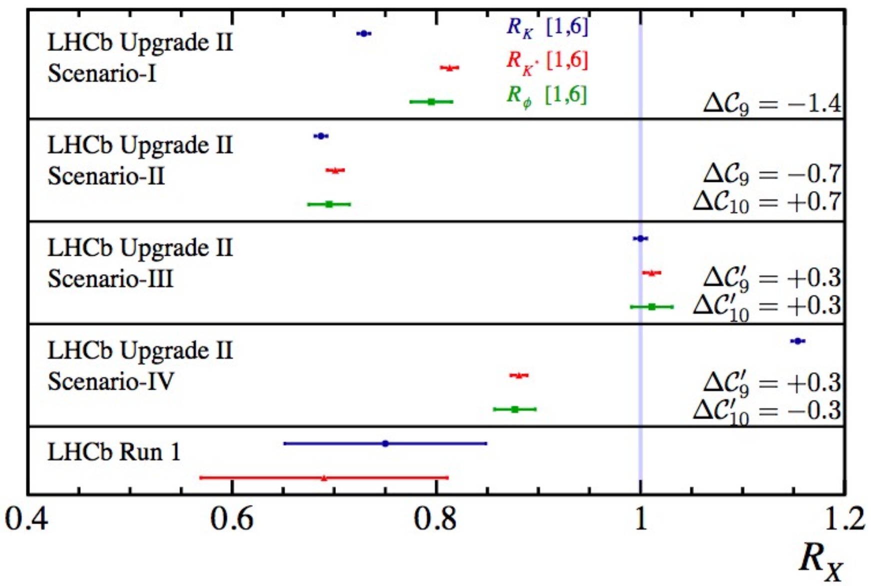
B-anomalies and neutrino interplay

- **Impact of lepton flavour universality violation on CP violation sensitivity of long baseline neutrino oscillation experiments** [https://arxiv.org/abs/1701.00327]
- **Combined explanations of B-physics anomalies: the sterile neutrino solution** [https://arxiv.org/abs/1807.10745]
- **Anomalies in (semi)-leptonic *B* decays and possible resolution with sterile neutrino** [https://arxiv.org/abs/1702.04335]
- **Leptoquarks in Flavour Physics and the anomalous magnetic moment of the muon** [https://arxiv.org/abs/1801.03380]
- **Synergy and complementarity between neutrino physics and low-energy intensity frontiers** [https://arxiv.org/abs/1712.05947]
- **B-physics anomalies: a guide to combined explanations** [https://arxiv.org/abs/1706.07808]
- **And many more!**

Upgrade II expectations for $R(K^{(*)})$

Nominal NP scenario

Right-handed components



Expected yields

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [272]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [273]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900

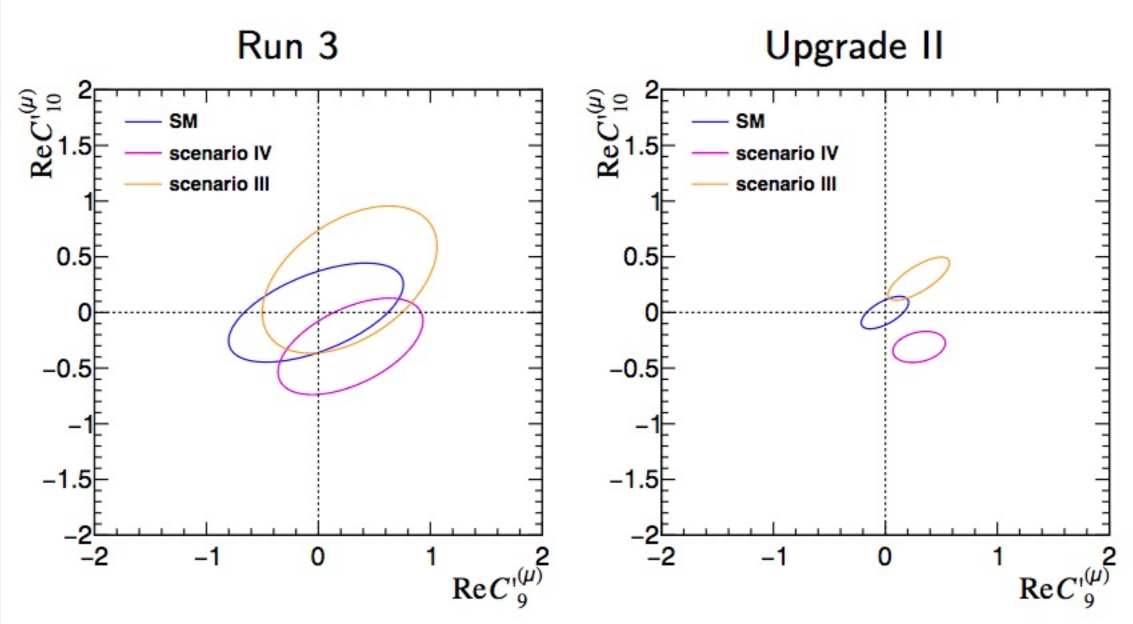
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [272]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [273]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Expected R_X uncertainties

[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-} \sim 46\,000$, $N_{K^{*0}e^+e^-} \sim 20\,000$
- Ultimate precision on R_{K,K^*} will be better than 1%
- Different R_X allow to probe different combinations of Wilson coefficients, separation of NP scenarios possible!
- Projections don't include improved ECAL for Upgrade II

Upgrade II sensitivity with $B^0 \to K^{*0}\mu^+\mu^-$



Scenario	$\mathcal{C}'_9$	$\mathcal{C}'_{10}$
SM	0	0
III	+0.3	+0.3
IV	+0.3	-0.3

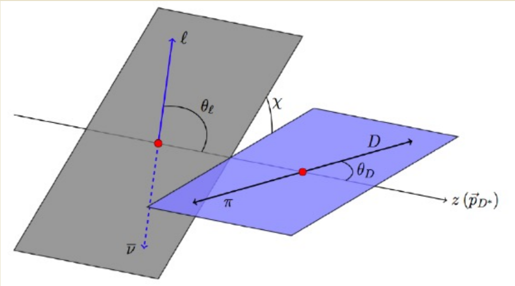
[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- Expect ~440 000 $B^0 \to K^{*0}\mu^+\mu^-$ candidates in Upgrade II (roughly Run 1 statistics for tree-level charmonia modes)
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated
- q^2-unbinned approaches allow to better exploit the data [JHEP 11 (2017) 176]

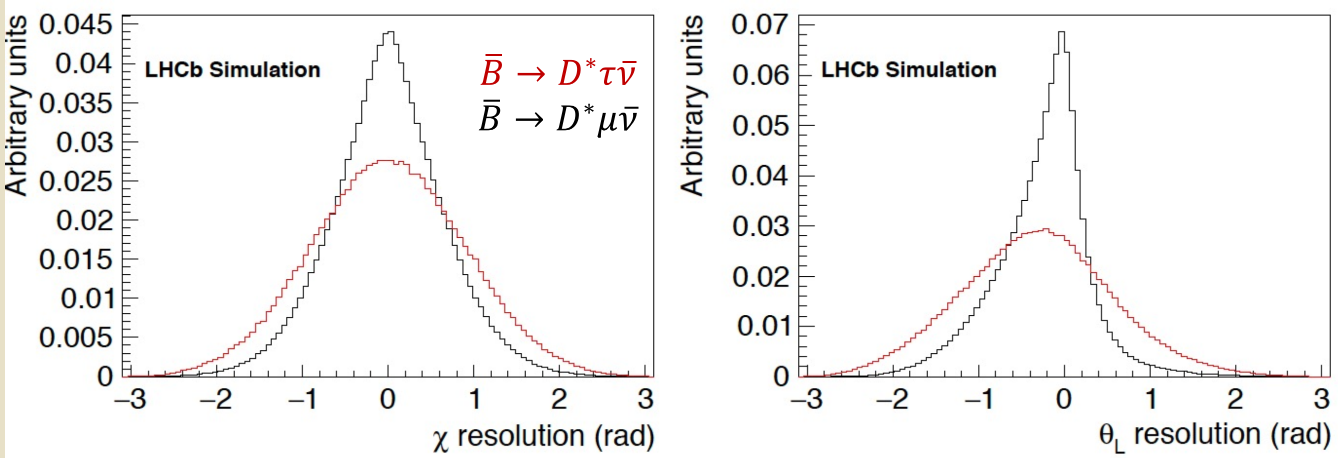
Upgrade II prospects

Upgrade II: new observables beyond the BF ratio

- Expect O(10 M) $\bar{B} \to D^{(*)}\tau\bar{\nu}$ candidates
- Sensitivity Upgr. II: σ(R_{D^*})/ R_{D^*}~1%
- Angular analysis would allow to determine spin structure of potential NP contribution



- Kinematics of $\bar{B} \to D^{(*)}\tau\bar{\nu}$ fully described by dilepton mass, and three angles, χ, θ_L and θ_d(better resolution)



Upgrade II: exploit other b-hadron species

- $\overline{B_s^0} \to D_s^{(*)+}\tau^-\bar{\nu}$: 6% (2.5%) relat. unc. after Run 3 (Upgrade II)
- Semitauonic decays of b-baryons and of B_c^+ mesons
  - $R(\Lambda_c^+)$ 4% (2.5%) relat. unc. after Run 3 (Upgrade II)

Lepton flavour (number) violation

- LFV branching fractions enhanced to 10^{-11} in certain models of leptoquarks, Z' [Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
- LHCb was the first experiment to search for LFV τ decays in a hadron collider

Searches for $B \to Ke\mu, B \to K^{*0}\tau(\to \pi\pi\pi\nu)\mu$, B $\to K\tau(\to \pi\pi\pi\nu)\mu$ and $\Lambda_b^0 \to \Lambda^0 e\mu$ are ongoing

- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \to Ke\mu$ and $B \to K^{*0}\tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables

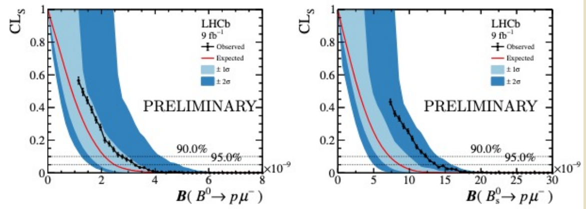
- Search for $B^0_{(s)} \to p\mu^-$

  (also Baryon number violating)

$\mathcal{B}(B^0 \to p\mu^-) < 2.6(3.1) \times 10^{-9}$ @90%(95%) C.L.

$\mathcal{B}(B^0_s \to p\mu^-) < 1.2(1.4) \times 10^{-8}$ @90%(95%) C.L.

LHCb-PAPER-2022-022 (in preparation)



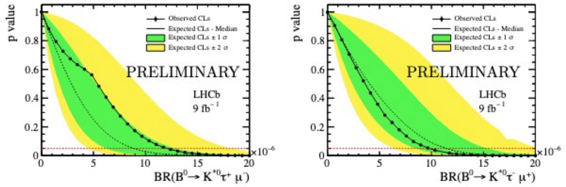
- Search for $B^0 \to K^{0*}\tau^{\pm}\mu^{\mp}$

  - partial $\tau^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}(\pi^0)\bar{\nu}_{\tau}$ reconstruction

$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$ @90%(95%) C.L.

$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6}$ @90%(95%) C.L.

LHCb-PAPER-2022-021 (in preparation)



- Search for $B^0 \to K^{0*}\mu^{\pm}e^{\mp}$ and $B^0_s \to \phi\mu^{\pm}e^{\mp}$

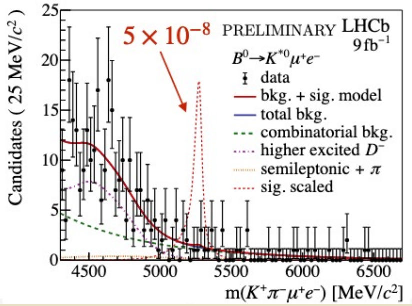
$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9) \times 10^{-9}$ @90%(95%) C.L.

$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9) \times 10^{-9}$ @90%(95%) C.L.

$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1(11.7) \times 10^{-9}$ @90%(95%) C.L.

$\mathcal{B}(B^0_s \to \phi\mu^{\pm}e^{\mp}) < 16.0(19.8) \times 10^{-9}$ @90%(95%) C.L.

LHCb-PAPER-2022-008



Prospects for selected flavour observables

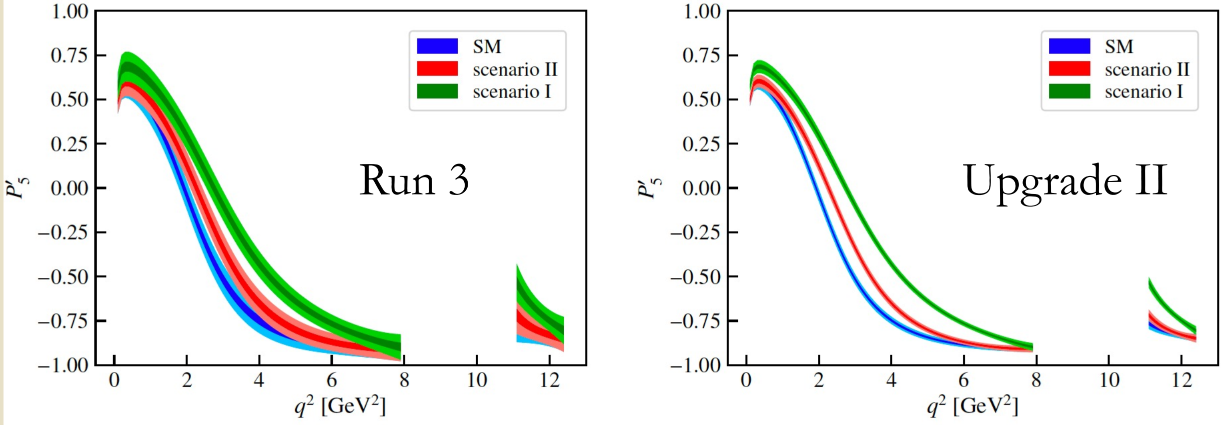
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c l^- \bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Based on extrapolations from current measurements, and take no account of detector improvements apart from an approximate **factor two increase in efficiency for hadronic modes**, coming from the full software trigger that will be deployed from Run 3 onwards.

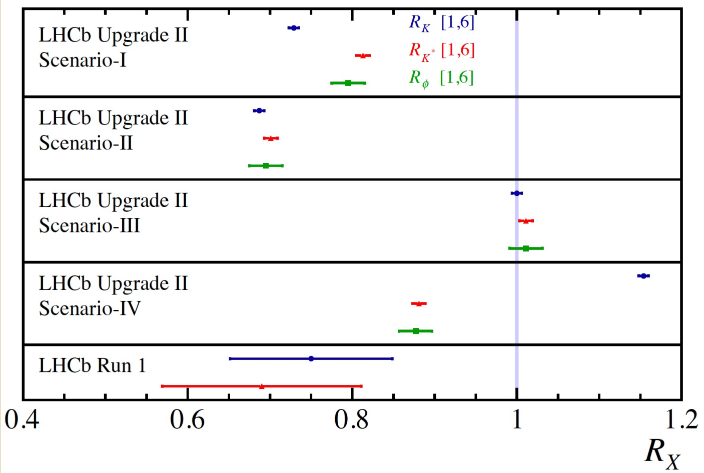
FCNC transitions

scenario	C_9^{NP}	C_{10}^{NP}	C'_9	C'_{10}
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3

- LFU will play a large role in Upgrade II physics case
- Improvements: Reduce the material (e.g. RF-foil), improve ECAL granularity, better Brem recovery algorithms
- Upgrade II: 440k fully reconstructed $B^0 \to K^{*0}\mu^+\mu^-$ will allow a q^2-unbinned approach ⇒ probe the SM contributions, NP expected to have no q^2 dependence
- Compare angular distr. $B^0 \to K^{*0}e^+e^-$/ $B^0 \to K^{*0}\mu^+\mu^-$



- Upgrade will provide thousands of $b \to d\ell^+\ell^-$ decays (e.g. 4300 $B_s^0 \to K^{*0}\mu^+\mu^-$), angular analysis possible
- 45k $B^+ \to K^+e^+e^-$ and 20k $B^0 \to K^{*0}e^+e^-$ in the Upgrade II → **Ultimate precision on $R_{K^{(*)}}$<1%**
- R_φ, R_{pK}, R_π, … will be possible un Upgrade II



All four NP scenarios could be distinguished at more than 5σ in Upgrade II!

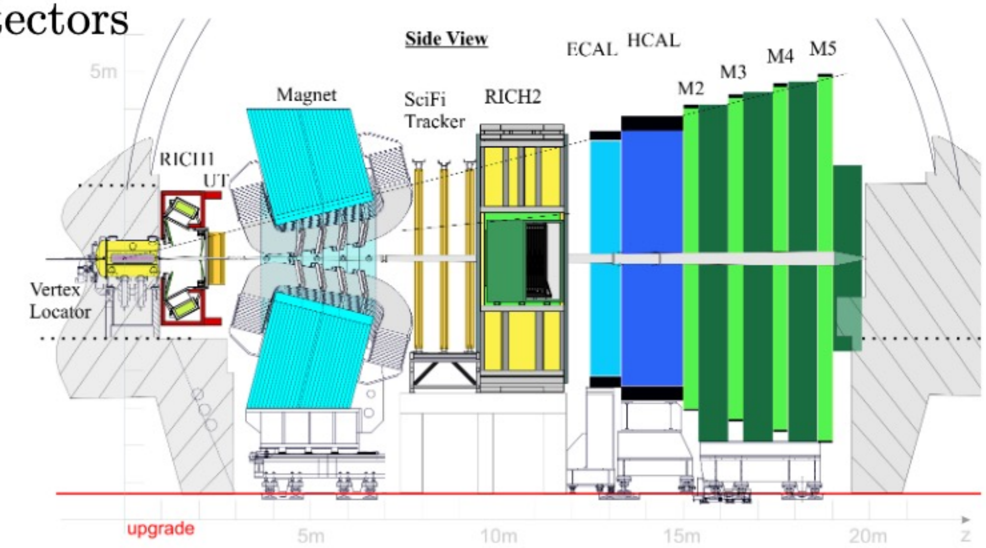
LHCb Upgrade I (Runs 3 + 4)

- Major upgrade of all sub-detectors

  $\rightarrow \mathscr{L}_{\text{peak}} = 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

  pile-up ≈ 5

  $\rightarrow$ fully software trigger for 40MHz readout



- New pixel-detector **VELO**
- New **RICH** mechanics, optics, photodetectors
- New Silicon strip upstream tracker **UT** (installation at end of year)
- New **SciFi** tracker
- New electronics for **MUON** and **CALO**
- New luminometer **PLUME**

Installed for operations in Run 3